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Welfare dynamics of innovations among agricultural households in Ghana: Implication for poverty reduction

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ABSTRACT

To reduce the high incidence of poverty in rural households, agricultural modernization using innovations has been pursued by governments and actors in the agricultural innovation system (AIS). This study analyzed how agricultural innovations and farmer-actor interactions in the AIS contribute to poverty outcomes among agricultural households in Ghana. Data used was the Ghana socio-economic panel survey data with 891 and 2595 observations for cocoa and maize households, respectively. The multinomial endogenous treatment effect model with instrumental variables was employed for the analysis. Adopting digital technologies in combination with other innovations, and having stronger farmer-actor interactions in the innovation system were associated with non-poor outcome in maize-growing households, who were poorer compared to cocoa-growing households. Innovations that consistently increased food security in both crop systems were associated with non-poor outcomes. The findings of the study highlight the need for governments and stakeholders to prioritize agricultural digitalization, encourage the adoption of multiple innovations and focus on food security-improving interventions as strategies to addressing rural poverty reduction.

1. Introduction

Globally, a country's agricultural sector plays a crucial role in rural transformation and overall economic development [1–3]. These roles are diverse and include food security, income security, employment generation, and poverty reduction, among others. Compared to the agricultural sector, growth in other sectors of an economy is envisaged to take time in completing the economic transformation process [4] since they do not employ the largest proportion of the population. Hence, growth in the agricultural sector is seen as one strategic way of achieving equity in economic transformation. Studies have demonstrated that agricultural growth and development is a key source of pro-poor growth in an economy, and could be thrice as effective for poverty reduction compared to growth in other sectors [5–7].

However, there are challenges in agricultural development and its role in developing countries. The sector has the challenge of feeding the world's population of about 9 billion and beyond [8] amidst the structural transformation occurring in most economies. Other challenges include the inadequacy and/or slow pace of technological innovation that will propel the sector to "catch up" with

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the growth experienced in other sectors [9]. Innovation in the agricultural sector has both direct and indirect effects on welfare [10]. The nature of the effect however depends on the pace at which the adoption of a set of innovations occurs; the household characteristics; the degree of market integration and liberalization; and the various support networks available to them [10]. The direct effect translates into productivity and revenue increases for adopters. The indirect effect on the other hand includes lowered food prices due to increased productivity; employment generation; and broad-based economic growth through production and consumption linkages with the non-farm economy [11,12]. Most studies have shown that the overall welfare effects have been positive in most instances [13–16]. Even in already developed economies, it has been found that adopting improved production methods have the potential of increasing the profits of producers and overall household income [17]. For Ghana, technological and policy change, observed from the development and adoption of improved cocoa seeds and the Cocoa Hitech Programme of government saw the promotion of improved seeds, agrochemical, and fertilizer application. This subsequently contributed to the overall productivity gains of the agricultural sector in Ghana as the cocoa sub-sector is a huge driver of the sector's growth [18]. These underscore the importance of innovation in improving welfare through productivity growth, with the country halving its poverty within that period.

By the end of the Millennium Development Goals (MDGs) era in 2015, Ghana was one of the few countries that had halved its national poverty incidence from 51.7% in 1991/1992 [19] to 24.2% in 2012/2013 [20]. The current poverty incidence stands at 23.4% [21], a slight decline from the 2012/2013 level [20]. Disaggregating poverty by employment shows that households engaged in agriculture have the highest poverty incidence of about 43%, compared to other economic engagements [21]. This is worrying as the current poverty level of agricultural households is a rise from the previous 39% [20]. It is however envisaged that in the 21st century, agriculture will remain fundamental to poverty reduction, economic growth, and environmental sustainability in agrarian countries, and innovation is expected to drive this process [22]. For Ghana to experience this shift, agricultural growth and development should be a strong policy focus. This includes investment in Science, Technology, and Innovation (STI) and strengthening the implementation of initiatives such as the Planting for Food and Jobs which aims at leveraging innovations such as improved seeds together with fertilizer subsidies to increase productivity. Efforts have also been made in Ghana's agricultural innovation development trajectory with the establishment of national research institutions, including universities of higher learning. The cocoa and maize sub-sectors for example have received heightened attention from both government and the private sector, due to their respective food and income security status in the country. Despite the development of technological innovations, and the contribution of these sub-sectors to food and income security, their potential yields (1 mt/ha for cocoa and 5 mt/ha for maize) have still not been achieved over the years and farmers continue to remain in poverty. This could be partly attributed to the slow pace of innovation development, among other factors.

For innovation to drive agricultural growth and stimulate poverty reduction, the interactions between actors and their innovative performance are key. Empirical evidence is however needed to establish how existing innovations and interactions between farmers and actors are contributing to households' welfare. Many studies have established the link between innovation and welfare and closely related to this study are that of [23,24]. However, the role of farmer-actor interactions in the innovation system has not received much attention. The interaction between actors is however needed to increase innovative performance and hence key to the innovation-welfare discourse. The study is also motivated by the endemic poverty incidence of agricultural households and the heterogenous impact of different innovations and crop types in improving the welfare of these households. Hence, we adopt multiple innovations and two crop regimes to test their effects on poverty outcomes. The consideration of multiple innovations in welfare analysis is evolving as recent works by Refs. [25,26] have focused on them. Renowned scholars like Rogers and Van de Ven have advocated for the consideration of multiple innovations in innovation studies due to their high reliability compared to studying a single innovation [27]. To the best of our knowledge, this is the first study that considers multiple crops and multiple innovations to establish the relationship between innovation and household welfare from an innovation system perspective.

This study sets out to investigate how the combination of innovations and farmers' interactions with innovation system actors contribute to poverty reduction through other welfare pathways among agricultural households. First, we analyse the effect of different combinations of innovations on household welfare and second, we examine how farmers' interactions with innovation system actors' impact on their welfare. The study postulates some implications for SDG 1 (reducing poverty in all its forms), SDG 2 (ending hunger and ensuring food security), and components of SDG 9 (industry, innovation and infrastructure). It provides options for addressing a key problem in African agriculture; which is poverty and the innovative interventions rolled out to reduce it. The study also answers a key question of whether innovations targeted at reducing poverty should be given in isolation or as a bundle and which welfare pathway is key to consequently reducing poverty with such interventions. Using a multinomial endogenous treatment model, we tackle this by considering three sets of innovations (improved seeds, digital and post-harvest innovations) with their combinations, and analysing each of them on different welfare indicators including poverty.

The paper is structured in five sections. Section 2 presents the theoretical and empirical review after the introduction in Section 1. The methodology adopted for the study is presented in Section 3 while Section 4 presents and discusses the results. Section 5 provides the concluding remarks with key policy implications of the study.

2. Theoretical and empirical review

The agricultural innovation system posits that innovations in agriculture usually occur within an interactive network of actors in both formal and informal settings. These interactions are open, which is a prerequisite for the innovative activity to take place, relying on all sources of knowledge and competencies [28]. The system perspective recognizes that innovation do not occur in isolation as it depends on a kind of collective action among the various actors as well as the opportunities that make utilization of these innovations possible [29,30]. The Agricultural Innovation System (AIS) then provides a framework for the analysis of agricultural innovations taking into cognizance the different and multiple collaborative actor interactions working towards institutional, managerial, and technological changes in agriculture, to increase innovative performance [31–34]. The innovative performance could be an improvement in productivity, food security, income, and poverty, among others, as focused on in this study.

[35] points out that the definition of innovation system and the methodological approach to its empirical studies is evolutionary as there is no fixed definition and methodology. Whilst some early innovation scholars [36] believe that there is a need to develop a common framework for analyzing the innovation system, others advocate for a more open and evolutionary approach [37]. The latter position can be said to form a central part of the competence-building components of the innovation system. By this, researchers who are part of the system are challenged to adopt new approaches to the concept. When the system perspective is recognized, it is shown to reflect the point that innovation is shaped by both institutional and social factors and not just structural factors that determine the trajectory of social and economic transformation [38].

Empirically, the AIS has been applied in varied ways, including assessing platform participation, production efficiency, adoption decisions, and value chains [39]. observed that extension, farmer groups, non-governmental organisations, and research, representing the networks farmers have created with these actors had a positive effect on technology adoption within the plantain value chain. On the other hand [40], found that in addition to these networks, policy support also played a role in technological impact. In the works of [39,40], the composite variable measuring the agricultural innovation system was equally found to have a positive effect on the adoption of innovations. Some studies have also found that participatory extension approaches have a positive impact on the economic welfare of participating farmers, compared to non-participating farmers [41–43]. In Tanzania however, a similar study on the impact of farmer field schools on food security and poverty reduction found that farmer field school had a significant positive impact on food security but no impact was observed on poverty reduction [42]. On the contrary, another study of farmer field schools on poverty in Eastern Africa revealed that participation in such programmes increased productivity and overall farm income by 61% [43]. As evolving as the innovation system methodological application is [35], it is important to explore what works and what proxies fit the construction of an innovation system.

Literature has established the effects of innovation on poverty reduction to be through the pathways of employment generation for both farm and non-farm economies; productivity, price, trade, and income effect; food and nutrition security effect; and growth linkage effect. These pathways are multifaceted and interactive and hence the poverty impact from agricultural innovations should not be looked at in a unidimensional way [10]. The price and income effects through productivity increase, arising from innovation are however noted to be one of the key pathways to poverty reduction and general welfare improvement in both rural and urban households [2,14,44]. However, this effect depends to a large extent on the market opportunities or tradability of the agricultural product in question [14], which otherwise might only impact poverty in terms of food security and not income. Smallholder farmers also benefit from increased revenue and reduced post-harvest losses, especially in cases where storage and agro-processing linkages are well established. The revenue scenario depends generally on the elasticity of output, price, and labour with respect to the particular technological change and whether the household is a net buyer or seller of an agricultural commodity in question [14]. Net buyers of agricultural produce usually experience positive welfare effects but the effect on net sellers (who are mostly the rural farmers) of agricultural produce depends largely on the relative elasticities [2,14]. In the case of a food crop commodity with a low degree of tradability, the net effect is the increase in available food for consumption and hence increasing food and nutrition security.

Productivity increase resulting from technological change could lead to a reduction in food prices and this increases the real incomes of net-buying households. The savings made can then be used to smoothen or diversify consumption, making poor households' nutritional status rich and counteracting malnutrition, especially in children [44–46]. Food poverty is one of the challenges faced by a rural population who are mostly agriculture-dependent and agricultural innovation could play a role in changing this trajectory [10, 46]. Studies have shown that the adoption of various agricultural innovations, especially that of improved seeds, improved inputs, and good agricultural practices, have the potential of increasing food security at the household level for farm families [47–49].

For specific types of innovations, a study on the effects of improved seeds of rice farming households in Nigeria, found a positive relationship between adoption and welfare, increasing household income by 46% and per capita expenditure by about 49%. In Nepal, it was also found that adopting modern varieties of maize and rice increased household welfare significantly [50,51]. Studies from other works on improved seeds equally point to the positive effects on farm households' food security, income, and poverty reduction [52–54]. This is consistent with the development literature on how agricultural innovations could help reduce poverty in agro-dependent economies [55,56]. [57] also found positive food security improvement effects from adopting improved maize seeds in South Africa. On the other hand, there is some evidence of an inverse relationship between the adoption of improved seeds and welfare. A study conducted by Ref. [58] posited that under stressed climatic conditions, locally bred varieties of crops performed better and had a poverty-reducing effect compared to modern improved varieties. About 12% of farm income have also been reported to be lost from the adoption of modern seeds [58]. Another study conducted in Uganda also found that the productivity and income effects were higher in the adoption of improved maize seeds but when combined with fertilizer a lower effect on income due to its high cost for poor farmers [56] was recorded. These suggest a possible heterogeneity in the effect of innovations on welfare depending on whether it is a single technology or a combination with others.

Findings from the effects of other innovations such as post-harvest technologies, Information, Communication Technology (ICT), and sustainable practices have seen similar trends [59]. found that household dietary diversity, food security, and child malnutrition improved with the adoption of improved storage technologies among Ethiopian agricultural households. The positive effects of a combination of all sustainable practices on income were however seen from the study of [57] relative to the sole adoption of the practices. Similar to Refs. [57,60] shown that combined innovations impact positively on several welfare outcomes including productivity, household incomes, and poverty, compared to single regimes. Using different ICT tools, including social media, mobile phones, and online search engines in measuring the impact of farm productivity in Chile [61], found that the use of mobile phones had the largest significant impact on the productivity of all the crops investigated, whilst the rest did not have any impact [62]. also found the use of a fleet management app impacted outputs positively compared to non-adopters.

These works have shown that the innovation-welfare pathway is heterogeneous depending on the crop type and innovation type under study and it will be imperative to consider the innovation-welfare nexus from that angle. However, most studies have not considered how different crop and innovation regimes could change the dynamics of welfare impact. Even for the studies that considered multiple innovations, the focus has primarily been on groups of similar technologies such as ICTs, conservation agriculture technologies, postharvest technologies and sustainable agricultural technologies. This study however considers different technologies along the agricultural value chain, such as improved seeds, post-harvest technologies, and ICT. Less attention has also been paid to applying the innovation system's perspective to understanding how farmer-actor interactions contribute to welfare improvement of agricultural households. This study therefore bridges these gaps by applying a system's perspective to assessing the role multiple innovations under different crop regimes play in welfare improvement of agrarian households.

3. Methodology

3.1. Data description

The paper uses the first two waves of the Ghana Socioeconomic Panel Survey (GSPS) data from the World Bank's Living Standard Measurement Survey (LSMS) database. The first wave was conducted in 2009/2010 and the second wave, 2013/2014, following the same data collection approaches. The survey adopted a two-stage stratified sampling approach based on the then 10 regions of Ghana. In the first stage of the strata sampling, the 2000 Ghana Population and Housing Census (GPHC) master sampling frame was used to select geographical clusters based on the regions of Ghana. This further resulted in the selection of 334 Enumeration Areas (EAs) from the regional clusters. A random selection of clusters from the EA list was done and a complete household listing was conducted to provide a frame for the next stage of the sampling. In the second stage of the sampling procedure, a simple random sampling of 15 households in each EA cluster was done.

A total of 5,009 households were interviewed in wave 1, out of which about 2,800 were agricultural households. In the second wave, a total of 4,774, out of which 2,463 were agricultural households due to the non-traceability of some of the households. The paper focused on two commodity cases; maize and cocoa since they are the major food and cash crop in Ghana, respectively. This resulted in further sub-sampling of the data and generated 463 and 428 cocoa households in waves 1 and 2, respectively, giving a total of 891 observations for the cocoa sub-sample. The maize household sub-sampling generated a total of 2,595 observations out of which 1,358 households were from wave 1 and 1,237 households from the second wave. Therefore, a total of 3,486 observations were used for this study.

3.2. Classifying innovations and (non)adopters

Following and adapting agricultural innovation classification from Refs. [23,63], the various set of innovations were grouped into the following:

3.2.1. Informationa/digital innovation

In this study, the use of mobile phones was used as a proxy for informational/digital innovation. Some farmers use their mobile phones to access production, weather, and marketing information using the services of mobile applications and telecommunication companies.

3.2.2. Post-production innovation

These were the innovations used in post-harvest handling such as improved storage facilities, which were mainly new and improved structures built to store produce.

3.2.3. Production innovations (Improved seeds)

In this study, improved seeds were used as a proxy for production innovation

3.2.4. Adopters/non-adopters

Farmers who responded "Yes" to the use of these sets of innovations were considered adopters and "No" were considered, "non-adopters" in each of the regimes. Since the study considered multiple innovations, there were multiple combinations of choices between the three innovations for the maize-growing households. The adoption regimes, where subscripts 1 and 0, represent adoption and non-adoption, respectively are represented below:

Regime 1. Adopters of Informational innovation (I) only with choice combinations of $I_1P_0S_0$

Regime 2. Adopters of Post-harvest innovation (P) only with choice combinations of $I_0P_1S_0$

Regime 3. Adopters of Improved Seeds (S) only with choice combinations of $I_0P_0S_1$

Regime 4. Adopters of I and P with choice combinations of $I_1P_1S_0$

Regime 5. Adopters of I and S with choice combinations of $I_1P_0S_1$

Regime 6. Adopters of P and S with choice combinations of $I_0P_1S_1$

Regime 7. Adopters of I, P, and S with choice combinations $I_1P_1S_1$

Regime 8. Non-adopters with choice combinations of $I_0P_0S_0$ (used as base for the analysis)

Achieving convergence for the cocoa models was difficult using all three sets of innovations since few cocoa farmers adopted post-harvest innovations. The combination of choices for cocoa farmers is hence given as:

Treatment 1. Adopters of Informational innovation (I) only with choice combinations of I_1S_0

Treatment 2. Adopters of Improved Seeds (S) only with choice combinations of I_0S_1

Treatment 3. Adopters of both with choice combinations of I_1S_1

Treatment 4. Non-Adopters of any of the two with choice combinations of I_0S_0 (Used as the base for the analysis)

3.3. Measurement of the welfare indicators

The study adopts the expenditure approach to measuring the poverty line since it is more appropriate compared to using other measures such as income [64]. This study uses farm revenue, food expenditure, non-food expenditure, and poverty headcount as the welfare indicators. Table 1 presents the description and measurement of the various welfare indicators used.

The household consumption expenditure in the study aggregated all the household expenditure, from various sources including money spent on gifts; food expenditure; the value of own produce; expenditure on clothes, fuel, education (fees, uniform, extra training, etc.), health (insurance, vaccination costs, etc.), and dwelling (water, electricity, construction, repairs, etc.). For this study, the total household expenditure was decomposed into food and non-food expenditure to get our money metric measure of food security, which is the food consumption expenditure (Table 1). The food consumption expenditure also includes the value of own produce consumed for the food crop (maize). These consumption metrics were calculated per adult equivalence and weighted at the household level.

Using the national poverty line of GHS 1,314.00 [20], a poverty headcount of each household was constructed using the Foster-Greer-Thorbecke (FGT) model, weighted at the household level, as illustrated in equation (1).

$$P_\alpha = \frac{1}{N}\sum_{i=1}^{q}\left(\frac{z - y_i}{z}\right)^\alpha \tag{1}$$

Where: P is the poverty measure (total household consumption expenditure)

α is the measure of poverty aversion of a household;
N is the sample size of the households;
z is the poverty line used which is set at GHS 1,314.00 by the Ghana Statistical Service; and
y is the welfare indicator; in this case the annual total household expenditure

The normalized gap of a poor person from the poverty line $\frac{z-y_i}{z}$ is used in the FGT estimation. The gap measures the expenditure shortfall as a share of the poverty line [65]. To measure the level of poverty incidence, the value of α plays a crucial role, with P_α measuring a population's poverty level. The value of α ranges between 0 and 2, with $\alpha = 0$ (P_0), measuring the proportion of the population that is poor, also known as the poverty headcount, the measure of interest in this study. However, $\alpha = 1$ (P_1) indicates the poverty gap, measuring the extent to which individuals on the average fall below the poverty line. The sum of the poverty gap score gives the minimum cost of eliminating poverty. Finally, $\alpha = 2$ (P_2), also termed the squared poverty measures the severity of poverty, which gives an indication of the level of inequality and deprivation in a given population [65]. As indicated by Ref. [65], α provides analysts and policymakers an opportunity to evaluate poverty from varying perspectives whilst accounting for distributional issues.

The study hypothesized that specific innovations under different crop regimes and the individual or collective interactions between

Table 1
Description and measurement of welfare indicators.

Welfare indicator	Description	Measurement
Farm revenue	The total revenue received from sales of farm produce	Value in GHS[a]
Food consumption expenditure (food security)	The total amount of money spent on food consumption, including the value of own production and purchases by the household, per adult equivalent. This also served as an indicator for food security.	Value in GHS
Non-Food consumption expenditure	The total amount of money spent on non-food commodities including rent, education, fuel transport cost, clothes, etc, per adult equivalent	Value in GHS
Poverty status	This variable measures whether a household is poor or not using the national poverty line of GHS 1,314.00 expenditure per annum per household.	Dummy (1 = poor; 0 = non-poor)

[a] GHS = Ghana Cedis, the legal currency of Ghana.

farmers and other actors in the agricultural innovation system will have heterogeneous effects on the poverty status and other welfare indicators of agricultural households.

3.4. Data analysis

3.4.1. Analytical framework

It is assumed that farmers self-select themselves into adopters and non-adopters of the various innovations, given observable and non-observable characteristics. The non-randomness of innovation decision renders it potentially endogenous and hence introduces an endogenous self-selection bias in the adoption decision which has to be corrected for. The Multinomial Endogenous Treatment Effect (METE) model as used by previous authors [23,26,66] was adopted to correct for the endogenous self-selection bias inherent in observational data. Using a pooled sample of adopters and non-adopters, and allowing for a dummy regression assumes that covariates have the same impact on the regimes of adoption. However, production factors have heterogeneous effects on household wellbeing outcomes and hence imply adoption regimes will have separate outcomes. It is, therefore, necessary to specify an outcome function for each of the adoption regimes whilst accounting for endogeneity. This is the main strength of the METE and other related models.

The METE is a two-stage estimation approach, where specific factors that drive adoption decisions are analyzed in the first stage using a binary choice model (logit or probit). The second stage then involves an estimation of the impacts of each of the innovation regimes on an outcome (welfare). To set up the MTE model for this study, each innovation regime had specified outcome equations simplified in Equation (2) as:

$$\text{Regime 1;}\quad y_{1i} = \alpha_1 X_{1i} + \mu_{1i}$$

$$\text{Regime 2;}\quad y_{2i} = \alpha_{2i} X_{2i} + \mu_{2i}$$

$$\text{Regime m;}\quad y_{mi} = \alpha_{mi} X_{mi} + \mu_{mi} \tag{2}$$

The outcome equation is conditioned on a selection equation to help deal with the selection bias inherent in the data and estimation procedure. The indirect utility ε *(V_{ij}*)* obtained from choosing among a set of multinomial choices is denoted by Equation (3):

$$\varepsilon V_{ij}^{*} = \alpha_j Z_i^{'} + \delta_j l_{ij} + \eta_{ij} \tag{3}$$

Where l_{ij} is a latent factor accounting for unobserved characteristics common to farmer i's treatment choice and outcome; δ_j are the parameters of the unobserved characteristics; α_j and η_{ij} are the parameters for the observed characteristics for the exogenous factors, $Z_i^{'}$, such that $l_{ij} \neq \eta_{ij}$.

The probability of treatment can then be represented in Equation (4) as:

$$\Pr(d_i|Z_i, l_i) = g\left(\alpha_1 Z_i^{'} + \delta_1 l_{i1} + \alpha_2 Z_i^{'} + \delta_2 l_{i2} \ldots\ldots \alpha_j Z_i^{'} + \delta_j l_{ij}\right) \tag{4}$$

Where g (.) follows an appropriate multinomial probability distribution. Specifically, in this study, the function g (.) is assumed to have a mixed multinomial logit structure given in Equation (5) as:

$$\Pr(d_i|Z_i, l_i) = \frac{\exp\left(\alpha_j Z_i^{'} + \delta_j l_{ij}\right)}{1 + \sum_{j=1}^{J} \exp\left(\alpha_j Z_i^{'} + \delta_j l_{ij}\right)} \tag{5}$$

The multinomial structure allows for unobserved heterogeneity across each farmer in their sensitivity to observed exogenous factors, giving a random coefficient structure. α is the parameter associated with the exogenous factors. *j* denotes the choice combination made, ranging from 1 to the *Jth* choice, which was 8 choices in total.

If the outcome, y_i is a count variable, where $y_i = 1 \ldots 4$ (farm revenue, food expenditure, non-food expenditure), the expected outcome equation for farmer ***i; i=1*** is formulated in Equation (6):

$$\varepsilon(y_i|d_i, X_i, l_i) = \beta X_i^{'} + \sum_{j=1}^{8} \gamma_j d_{ij} + \sum_{j=1}^{8} \lambda_j l_{ij} \tag{6}$$

where: $\varepsilon(.)$ is a function of each of the latent choices of innovation regimes, l_{ij}; j = 1 … 8. This function implies that the outcome is affected by the unobserved characteristics also affecting the selection into treatment, represented by Equation (4). X_i s are the exogenous covariates; γ_j are the treatment effect relative to the control group, which in this study is non-adopters, the 8th regime, $I_0P_0V_0$; and λ_j are the factor loading parameters for each treatment. If λ_j is positive, then treatment (the adoption choice) and outcome are positively correlated through the unobserved characteristics leading to a positive selection effect. A negative selection effect is however the case if λ_j is negative [67]. The significance of λ_j indicates the presence of a selection bias in the model, which has to be corrected for.

The 5th outcome, poverty which is a binary variable measuring whether a farm household is poor or non-poor requires the assumption of a negative binomial distribution, with a density function, *f* specified in Equation (7) as:

$$f(y_i|d_i\,X_i\,I_i) = \frac{\Gamma\,(y_j+\psi)}{\Gamma(\psi)\Gamma(y_i+1)}\left(\frac{\psi}{u_i+\psi}\right)^{\psi}\left(\frac{u_i}{u_i+\psi}\right)^{y_i} \tag{7}$$

Where $u_i = \varepsilon(y_i|d_i\,X_i\,I_i) = \exp\,(\beta X_i^{'} + \gamma d_i^{'} + \lambda I_i^{'})$.

u_i is the utility obtained based on the outcome given the adoption scenarios and; $\psi = \frac{1}{\alpha}$; $\alpha > 0$ is the overdispersion parameter. This model is usually identified when the exogenous factors in the selection models are the same as those in the outcome models. However, it is always preferred to identify the model using an exclusion restriction by including some variables that serve as instruments in the treatment model but not the outcome model. In this study, access to agricultural information was used as the instrument. This variable is likely to affect adoption decisions but not directly on welfare/poverty. The selected variable to serve as instruments were admissible through the performance of a falsification test as done in previous studies [26,66].

As indicated in Refs. [68,69], a joint distribution for the outcome and treatment variables need to be obtained since they are simultaneously estimated, given in Equation (8) as:

$$\Pr(y_i\;d_i|X_i\;Z_i,I_i) = f(y_i|d_i\;X_i\;I_i).\;\Pr(d_i|Z_i,l_i) = h \tag{8}$$

3.4.2. Model specification

Adopting the METE to this study, a linear expression of the relationship between exogenous factors (Z); innovation (I); and welfare indicators (y_i) of a household following Khonje, Manda [19]is given in Equation (9). It is modified to include an indicator for the agricultural innovation system (N) and individual actor interactions (A). It is also extended to capture multiple innovation regimes and an instrument, S. The innovations included Informational innovation, ICT (I_i); Post-production innovation (P_i); production innovation, improved variety (V); and their combinations. Conditioning the outcome function on the adoption of any of the treatments based on the specified choice bundles, the multinomial treatment effect model for the study is expressed in Equation (9):

$$y_i = \theta Z_i + \varphi_i \sum_{i=1}^{8} I_i + \beta_i \sum_{i=1}^{6} A_i + \delta N_i + \sigma S + \mu \tag{9}$$

Where:

y_1 = Farm revenue;
y_2 = food expenditure;
y_3 = non-food expenditure;
y_4 = poverty status.

The MTE for cocoa on the other hand was specified as given in Equation (10) with similar notational definitions as in Equation (9).

Table 2
Variable description in the multinomial treatment effect model.

Variable	Description	Measurement
Household size (Z_1)	The total number of people in a household	Number
Year (Z_2)	Period data was taken	Dummy (0 = 2010; 1 = 2014)
Age (Z_3)	Age of farmer in years	Years
Education (Z_4)	Whether a farmer had had formal education or not	Dummy (0 = no; 1 = yes)
Gender (Z_5)	Sex of the farmer	Dummy (0 = female; 1 = male)
Agricultural information (Z_6)	Access to agricultural information which served as the instrumental variable for the model	Dummy (0 = yes; 0 = no)
Household asset (Z_7)	The value of assets owned by the household	Value (GHS)
Productivity (Z_8)	Yield of farmers	Kilogram per hectare (kg/ha)
Market (A_1)	Farmer's linkage with market actors side farm gate	Dummy (1 = yes; 0 = no)
Financial service (A_2)	Farmer's access to financial services	Dummy (1 = yes; 0 = no)
Policy support (A_3)	Farmer's access to government's fertilizer subsidy and cocoa mass spraying programmes	Dummy (1 = yes; 0 = no)
Farmer Based Organisation (FBO) (A_4)	Farmer's membership and interaction in an FBO	Dummy (1 = yes; 0 = no)
Non-Governmental Organisation (NGO) (A_5)	Farmer's interaction with NGOs	Dummy (1 = yes; 0 = no)
Extension (A_6)	Farmer's interaction with extension agents	Dummy (1 = yes; 0 = no)
AIS (N)	The intensity of farmers interaction with actors in the AIS.	Count (0 = none (lowest); 1 = one actor (lower); 2 = two actors (low); 3 (medium) = three actors; 4 = four actors (high); 5 = five actors (higher); 6 = all six actors (highest)

$$y_i = \theta Z_i + \varphi_i \sum_{i=1}^{4} I_i + \beta_i \sum_{i=1}^{6} A_i + \delta N_i + \sigma S + \mu \tag{10}$$

$\varnothing_i$, are the coefficients measuring the impact of the individual innovations and their combinations. θ is the coefficient measuring the effects of a myriad of exogenous factors influencing the welfare of households. These exogenous factors and network characteristics included in the model are described in Table 2.

β_i are the coefficients measuring the individual actor interactions with farmers.

δ measures the effect of the interaction intensity of farmers in the agricultural innovation system. The intensity of interaction is measured as the sum of the total number of actor interactions a farmer has, ranging scores of 0 to 6. The higher the score the stronger a farmer is connected in the network, and vice versa.

σ is the coefficient measuring the effect of the instrument, S, used; which is access to agricultural information. It is believed that access to agricultural information from colleague farmers and other sources could influence adoption decisions but will not directly affect poverty and other welfare indicators. A falsification test of agricultural information as an instrument was conducted to ascertain this.

The proxy index measuring AIS in the model was the number of actors (A_i) each farmer interacted with, which generated a score ranging from 0 to 6, presented in Equation (11) as:

$$N_i = \sum_{i=0}^{6} A_i \tag{11}$$

The higher the number, the higher the intensity of a farmer's interaction in the innovation system. As a result, two models were estimated for each welfare indicator. Model 1 was the model with farmers' interactions with individual actors and Model 2 was the model that controlled for the intensity of farmers' interactions with actors, as the AIS index.

4. Results and discussion

4.1. Temporal and crop-specific poverty scores

Between 2010 and 2014, the overall poverty incidence for the households that cultivated maize and cocoa was estimated at 44%, with cocoa-producing households having a relatively lower incidence of poverty (35%) compared to maize-producing households recording 47% (Fig. 1).

Disaggregating by sector, cocoa growing households' poverty incidence was a few points below the national poverty incidence of the entire agricultural sector, which stood at 39% in 2013 [20] and 43% in 2017 [21]. Poverty incidence for maize households on the other hand was higher than the national poverty incidence. However, for the 2014 poverty levels, that of cocoa households was far lower (28%) than the national agricultural poverty incidence of 43%, whilst maize was very close (42%) to the national figure.

Table 3 shows the temporal and crop-specific FGT scores. Cocoa has the potential of generating higher incomes [70], which can be channeled into consumption decisions, compared to a food crop such as maize. This implies that the cash crop sub-sectors have a relatively lower poverty incidence compared to the food crop sub-sector. The high poverty incidence being recorded in the agricultural sector may be driven largely by the food crop sub-sector as found in Ref. [21]. This notwithstanding, it is commendable to note that poverty incidence reduced between 10 and 12% points for both crop households between 2010 and 2014, with cocoa farm households experiencing a relatively larger decline than maize households.

4.2. Test for the exogeneity of treatment and the instrumental variable

The test for exogeneity of treatment and outcome was conducted through the factor loading parameter, lambda (λ) in the model set up for both cocoa and maize farmers, as presented in Appendices 1 and 2. The results presented suggest that there are both negative and positive selections for all the innovation regimes and outcomes. These unobserved characteristics potentially influence the adoption decision negatively or positively.

Even though not all the selection terms were significant for all the models, each of the adoption regimes had a significant selection

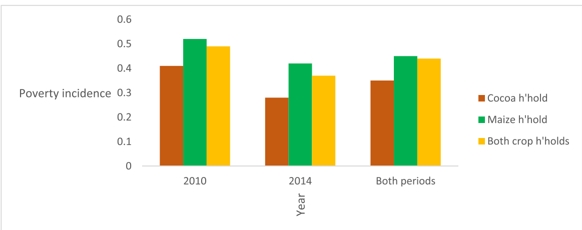

Fig. 1. Crop-specific poverty incidence across time.
Source: Authors' computation based on 2009/2010 and 2013/2014 GSPS data (2021).

Table 3
Temporal and Crop specific FGT scores.

	$\alpha = 0$ (Poverty headcount)				$\alpha = 1$ (Poverty gap)			$\alpha = 2$ (Poverty severity)		
Crops		Pooled	Cocoa	Maize	Pooled	Cocoa	Maize	Pooled	Cocoa	Maize
		0.44	0.35	0.47	0.16	0.13	0.18	0.08	0.06	0.09
Years	2010	0.49	0.41	0.52	0.19	0.16	0.21	0.10	0.08	0.11
	2014	0.37	0.28	0.42	0.13	0.09	0.15	0.06	0.04	0.08
		Pooled	0.25	0.75		0.24	0.76		0.22	0.78

Source: Authors' computation based on 2009/2010 and 2013/2014 GSPS data (2021)

term in at least one model. This suggests that not accounting for these unobserved characteristics could render some of the estimates biased, due to the presence of self-selection of farmers into treatment and control groups. This also supported the use of the multinomial endogenous treatment model for the analysis.

To correct for the self-selection bias and endogeneity observed in the data, access to agricultural information was used as an instrument. From Appendices 3-6, it can be observed that accessing agricultural information did not have a significant effect on any of the outcome variables for non-adopters, but had a significant effect on the adoption of all innovation regimes except for improved seeds. Access to agricultural information hence served as an appropriate instrument for the analysis.

4.3. Factors influencing the welfare of farm households

4.3.1. Effects of innovations on household welfare

In this section, the treatment effect of each innovation bundle on the various welfare indicators is discussed as presented in Table 4 (for cocoa) and Table 5 (for maize). Cocoa farmers who adopted only informational innovation had a significant positive welfare effect with all the indicators but surprisingly were associated with poor household status (Table 4). Maize farmers who adopted only informational innovation also had a significant positive non-food effect but a non-significant poverty effect (Table 4).

These were unexpected given the role that digitalization plays in the modern farm economy. However, the complementarities of innovations could account for this finding since some innovations may need others to work for the benefit of the end-user. As suggested by Ref. [71], for digital innovations to drive agricultural transformation through welfare improvement, strengthening ICT systems to encourage adoption and efficient utilization will be required. There is a great potential for growth and poverty reduction in the agricultural sector to occur through digitalization and so should be prioritized.

Farmers who adopted only postharvest innovations for maize experienced a significant increase in farm revenue, reduced non-food expenditure, and increased the probability of being poor. Farmers with improved postharvest facilities could store their products in anticipation of favourable market conditions and also meet household food needs. Therefore, temporarily, the household may suffer low purchasing power for non-food expenditure since income from the produce may be held up in-store. However, in the long run, it may improve their non-poor outcomes with the increase in crop revenue.

The non-significance of improved seeds to welfare is surprising and contrary to apriori expectations given that such innovations are developed and promoted by Research and Development (R&D) institutions and the Ministry of Food and Agriculture. Contrary to this finding [66,72], found significant positive welfare effects of improved seed variety adoption. Other works have also found a counter effect of improved variety over local variety on farmers' welfare [58]. Farmers are known to recycle improved seeds from the first production, leading to loss of vigour once replanted and this could contribute to the current finding. This presupposes that the dissemination of innovations has to accompany continuous awareness and sensitization through intensive extension education as

Table 4
Treatment effects of innovation on the welfare of cocoa farming households.

	Farm revenue 1	Farm revenue 2	Food exp. 1	Food exp. 2	Non-food exp. 1	Non-food exp. 2
I_1S_0	1.266***	1.181***	0.235	0.326***	0.745***	0.667**
	(0.291)	(0.258)	(0.430)	(0.087)	(0.214)	(0.303)
I_0S_1	−0.867	0.110	−0.067	−0.166	0.137	−0.276
	(0.605)	(0.319)	(0.133)	(0.124)	(0.285)	(0.241)
I_1S_1	0.801**	1.793***	0.025	0.096	0.255	0.898***
	(0.386)	(0.277)	(0.134)	(0.105)	(0.212)	(0.340)

	Poverty 1	Poverty 2
I_1S_0	0.027	0.029*
	(0.200)	(0.078)
I_0S_1	0.235	0.234*
	(0.230)	(0.130)
I_1S_1	−0.185	−0.145
	(0.173)	(0.108)

Standard errors in parentheses; $*p < 0.10$, $**p < 0.05$, $***p < 0.01$.
Model 1 = model with individual actor interactions; Model 2 = model with the intensity of actor interactions as sum of the individual interactions.
Source: Authors' computation based on the 2009/2010 and 2013/2014 GSPS data (2021)

Table 5
Treatment effects of innovation on household welfare of maize farming households.

Innovation regime	Farm revenue model 1	Farm revenue model 2	Food exp. model 1	Food exp. model 2	Non-food exp. model 1	Non-food exp. model 2
$I_1P_0S_0$	−0.227***	−0.238***	0.040	0.025	0.607***	0.613***
	(0.063)	(0.068)	(0.115)	(0.105)	(0.197)	(0.193)
$I_0P_1S_0$	0.264***	0.264***	0.200	0.220	−0.525**	−0.540***
	(0.053)	(0.056)	(0.183)	(0.153)	(0.211)	(0.188)
$I_0P_0S_1$	0.097	0.059	−0.051	−0.079	0.012	0.041
	(0.077)	(0.080)	(0.111)	(0.111)	(0.321)	(0.309)
$I_1P_1S_0$	−0.032	−0.034	0.017	0.011	0.362	0.373
	(0.052)	(0.054)	(0.121)	(0.108)	(0.311)	(0.344)
$I_1P_0S_1$	−0.040	−0.051	0.187	0.169	0.671***	0.673***
	(0.062)	(0.071)	(0.117)	(0.116)	(0.245)	(0.257)
$I_0P_1S_1$	0.024	0.019	0.180	0.183	−0.193	−0.216
	(0.064)	(0.067)	(0.124)	(0.115)	(0.257)	(0.224)
$I_1P_1S_1$	0.173***	0.169***	0.185	0.185*	0.137	0.160
	(0.058)	(0.060)	(0.114)	(0.110)	(0.227)	(0.194)
Innovation regime			**Poverty model 1**			**Poverty model 2**
$I_1P_0S_0$			−0.071			−0.076
			(0.081)			(0.080)
$I_0P_1S_0$			0.278***			0.275***
			(0.075)			(0.080)
$I_0P_0S_1$			0.141			0.144
			(0.096)			(0.105)
$I_1P_1S_0$			−0.065			−0.058
			(0.058)			(0.059)
$I_1P_0S_1$			−0.063			−0.059
			(0.065)			(0.068)
$I_0P_1S_1$			−0.029			−0.031
			(0.069)			(0.070)
$I_1P_1S_1$			−0.119*			−0.125**
			(0.061)			(0.059)

Standard errors in parentheses; $*p < 0.10$, $**p < 0.05$, $***p < 0.01$.
Model 1 = model with individual actor interactions; Model 2 = model with the intensity of actor interactions as the sum of the individual interactions.
Source: Authors' computation based on the 2009/2010 and 2013/2014 GSPS data (2021)

farmers may not follow full protocols. Accompanying measures and complementarities are always critical to the success of every adoption process which supports assertions by earlier works, including [73,74].

Whilst the single adoption of improved seeds did not affect welfare, its combination with informational innovation ($I_1P_0S_1$) improved the welfare of households through revenue and non-food expenditure effects. Though the food security effect was positive, it was not significant for both crop households. A negative revenue effect from this combination ($I_1P_0S_1$) but a positive non-food expenditure effect was observed in maize households (Table 5), similar to cocoa households in Model 2 (Table 4). The interplay of all these mediating welfare indicators, however, did not contribute significantly to poverty reduction, with the adoption of $I_1P_0S_1$ in both crop households. Due to the interconnectedness of the different welfare pathways, a counter-effect in any of them could inhibit the effect on poverty, the ultimate outcome.

Finally, maize farmers who adopted all three combinations of innovations; informational, postharvest, and improved seeds ($I_1P_1V_1$) observed significant positive farm revenue, food security, and non-poor effect. This is consistent with the findings of [26], which posited that joint adoption of innovations had larger poverty reduction effects as opposed to adopting single innovations. This goes to support the earlier assertion on the need for innovations to be bundled or packaged for desired outcomes. The food security effect of the different sets of innovations appeared to be non-significant in earlier innovation regimes but it can be observed that adopting all sets of innovations, significantly increased maize households' food security by about 18.5% (Table 5). Significant non-poor outcome was also observed for maize-growing households that adopted the full set of innovations ($I_1P_1S_1$). On the other hand, there is a non-significant poverty effect among cocoa-growing households with their respective full set of innovations (I_1S_1). By implication, though cocoa-growing households recorded lower poverty incidence compared to maize-growing households, the impact of innovation on non-poor outcomes was significant among maize households. However, the food security effects of innovations on either cocoa, as a cash crop, or maize, as a food crop, remained inconclusive as there were no major differences between the two. However, innovations that increased food security in both households equally resulted in non-poor outcomes.

4.3.2. Effects of innovation system characteristics on welfare

Table 6, 7, and 8 present findings on the factors influencing farmers' welfare. The main factors considered are market, financial actors, policy support, farmer associations, extension, and agricultural innovation system interaction.

4.3.2.1. Market interaction. In Ghana, there is a defined market outlet for cocoa producers but the maize market is not well defined and farmers usually seek market outlets for their produce. The study found that maize farmers with strong linkages with market actors are associated with significant positive revenue and expenditure effects (Table 6). Subsequently, these farmers were also seen to have significant non-poor outcomes, compared to farmers who only sold at the farm gate and community markets by themselves. The same was however not recorded for cocoa-growing households. The work of [75] also found a positive and significant effect of market participation on the welfare of maize farmers in Tanzania. Markets in the cocoa sector have however been found to improve the welfare of farmers if it is linked to sustainable value chain development, as indicated in Ref. [76]. This implies that for such a defined market to improve welfare, there will be the need to restructure the market and expand the value chain [77]. have also suggested supporting marginalized farmers with market linkages to enhance commercialization to improve welfare and reduce inequality.

4.3.2.2. Financial actors' interaction. The study revealed that farmers' access to financial services significantly increased non-food expenditure (Table 7), but did not affect food expenditure (food security) in both maize and cocoa households (Table 6). In terms of poverty, having access to and interacting with financial service actors, resulted in non-poor outcomes, particularly for maize households (Table 8). The effect at the pooled farm household level also indicates a significant non-poor effect with a farm household's interaction with financial service providers. This, therefore, suggests that farmers who are linked to financial institutions have a higher likelihood of being non-poor, which is observed in similar studies [78–80]. The positive welfare effects of financial services are mainly from non-food consumption and not from revenue effects from farm activities. Farmers may contract financial services not necessarily to meet production needs but to smoothen other household consumption needs. Financial institutions however play a key role in the AIS from knowledge generation to diffusion, and improving the welfare of all value chain actors [81] and so interaction with such actors is key.

4.3.2.3. Policy support. Findings indicate that policy support significantly increased the revenue levels of maize-growing households but had a revenue-reducing effect among cocoa households (Table 6). Subsequently, the poverty effect due to policy is contrary to our expectations for both crop households. This finding was not expected but also speaks to the implementation challenges of the fertilizer subsidy policy programme as highlighted in Ref. [82]. One can see that potentially, the policy support programmes could contribute to positive welfare outcomes through revenue effects, especially for the maize sub-sector if the bottlenecks in implementation such as delays in delivery to farmers and the smuggling of subsidized fertilizers to neighbouring countries are removed.

4.3.2.4. Farmer based organisations (FBOs), non-governmental organisations (NGOs), and extension interactions. FBOs are usually created to bring farmers together to access some form of support from both government and private sectors. The findings indicate that belonging to an FBO or an NGO network did not positively influence the welfare outcomes of farmers, especially maize farmers. On the other hand, belonging to an FBO rather increased the likelihood of being poor for cocoa-growing households. Similar findings were obtained by Refs. [26,83] where cooperatives and group membership had a non-significant effect on farmers' welfare. Given that FBOs were mostly established by NGOs, it was not surprising that the effect of NGOs on welfare followed a similar pattern as FBOs. Promoting self-help programmes and providing technical assistance could be one pathway to improving welfare outcomes.

Farmers who interacted with extension service providers however recorded reduced farm revenue effect but increased food security among all crop households (Table 5) and subsequently resulted in non-poor outcomes of maize households and the pooled model (Table 7). It is important to highlight the significant effect on the food security effect of farmers by extension interactions which is a

Table 6
Effects of innovation system Characteristics on Farm Revenue and Food expenditure (security).

	Revenue model 1		Food exp. model 1		Revenue model 2		Food exp. model 2	
	Maize	Cocoa	Maize	cocoa	Maize	cocoa	Maize	cocoa
Market	0.153***	−0.327**	0.134***	−0.060				
	(0.044)	(0.155)	(0.032)	(0.096)				
Finance	−0.234***	−0.037	0.032	0.029				
	(0.041)	(0.132)	(0.030)	(0.046)				
Policy	0.527***	−0.091	0.001	0.010				
	(0.079)	(0.185)	(0.060)	(0.059)				
FBO	−0.161**	0.353	−0.060	−0.177*				
	(0.079)	(0.483)	(0.049)	(0.101)				
NGOs	0.057	0.193	0.018	−0.107				
	(0.064)	(0.160)	(0.045)	(0.075)				
Extension	−0.002	−0.494	0.286***	0.201**				
	(0.065)	(0.391)	(0.039)	(0.092)				
AIS index					0.087***	−0.009	−0.022	−0.077
					(0.014)	(0.019)	(0.020)	(0.051)
Constant	5.363***	4.480***	7.676***	8.168***	7.492***	7.861***	5.406***	4.274***
	(0.160)	(0.499)	(0.101)	(0.175)	(0.141)		(0.150)	(0.436)
Observations	2595	891	2595	891	2595	891	2595	891

Standard errors in parentheses; $^{*}p < 0.10$, $^{**}p < 0.05$, $^{***}p < 0.01$.
Model 1 = model with individual actor interactions; Model 2 = model with the intensity of actor interactions as the sum of the individual interactions.
Source: Author's computation based on the 2009/2010 and 2013/2014 GSPS data (2021)

Table 7
Effects of Innovation System Characteristics on Household Welfare-Non-food expenditure.

	Non-food model 1		Non-food Model 2	
	Maize	Cocoa	Maize	Cocoa
Market	0.108*	0.083		
	(0.056)	(0.121)		
Finance	0.115**	0.173*		
	(0.053)	(0.089)		
Policy	0.001	−0.330**		
	(0.119)	(0.128)		
FBO	−0.042	−0.241		
	(0.089)	(0.179)		
NGOs	0.059	0.059		
	(0.060)	(0.101)		
Extension	0.030	0.128		
	(0.079)	(0.171)		
AIS			0.074***	−0.020
			(0.014)	(0.024)
Constant	5.930***	6.935***	7.899***	8.481***
	(0.214)	(0.350)	(0.099)	(0.169)
Observations	2595	891	2595	891

Standard errors in parentheses; $*p < 0.10$, $**p < 0.05$, $***p < 0.01$.
Model 1 = model with individual actor interactions; Model 2 = model with the intensity of actor interactions as the sum of the individual interactions.
Source: Authors' computation based on the 2009/2010 and 2013/2014 GSPS data (2021)

Table 8
Effects of Innovation System Characteristics on Household Welfare-Poverty incidence.

	Poverty model 1		Poverty model 2		Poverty pooled	
	Maize	Cocoa	Maize	Cocoa	Model 1	Model 2
Market	−0.036*	0.072			−0.028	
	(0.021)	(0.051)			(0.020)	
Finance	−0.037*	−0.047			−0.043**	
	(0.020)	(0.035)			(0.020)	
Policy	0.081*	0.073			0.039	
	(0.043)	(0.055)			(0.035)	
FBO	0.021	0.125*			0.044	
	(0.035)	(0.074)			(0.031)	
NGOs	0.010	0.021			0.008	
	(0.032)	(0.060)			(0.026)	
Extension	−0.134***	−0.081			−0.114***	
	(0.028)	(0.062)			(0.025)	
AIS			−0.036***	0.010		−0.022***
			(0.009)	(0.014)		(0.008)
Constant	0.320***	0.036	0.420***	0.143	0.330***	0.387***
	(0.073)	(0.149)	(0.066)	(0.120)	(0.074)	(0.058)
Observations	2595	891	2595	891	3486	3486

Standard errors in parentheses; $*p < 0.10$, $**p < 0.05$, $***p < 0.01$.
Model 1 = model with individual actor interactions; Model 2 = model with the intensity of actor interactions as the sum of the individual interactions.
Source: Authors' computation based on the 2009/2010 and 2013/2014 GSPS data (2021)

very important welfare indicator among agricultural households as similarly established in previous works [23,84].

4.3.2.5. Agricultural innovation system interaction. Heterogeneous effects of AIS on the welfare of cocoa and maize-growing households were observed in the study. Cocoa-growing households did not observe any effect of AIS interactions on their welfare. In Ghana, there is no cocoa innovation platform through which interactions occurred and so interaction occurred on a bilateral basis with individual actors. This could potentially hinder the impact of AIS in the cocoa sector as observed. It is however worth mentioning that efforts are underway to re-establish the cocoa innovation platform by the Ghana Cocoa Board, through collaboration with the private sector [85]. This could restore the strength and impact of the cocoa innovation system.

Contrary to the findings obtained for the cocoa innovation system, the maize innovation system recorded positive and significant effects on all welfare indicators, but for farm revenue. Having a stronger network interaction within the maize innovation system significantly increased food and non-food expenditures. Subsequently, farmers with stronger network interactions within the maize innovation system had significant non-poor effects, compared to those who had weaker or no interactions. Significant poverty reduction effects of innovation systems have also been observed by the few studies in this area [86]. Knowing how vulnerable the food crop sub-sector is to markets, postharvest handling, and weather failures, it is encouraging to know that having stronger linkages in the innovation system, can improve welfare and result in non-poor outcomes. These actors could even serve as a buffer, potentially cushioning them against random shocks through the provision of supportive structures and systems, which is one key merit of innovation networks [87,88].

4.3.3. Discussion of findings within a policy framework

The findings of our study have several policy implications. Firstly, the effect of informational innovation puts a spotlight on the importance of agricultural digitalization in enhancing farmers' welfare. This calls for policies toward the digitalization of agricultural activities (e-agriculture) which has also been emphasized in Ref. [89]. The heterogeneous findings notwithstanding, innovation systems have the potential of influencing poverty reduction and other welfare indicators of farmers. There is the need for a coordinated effort in ensuring that the innovation systems of both commodities function through the use of innovation platforms to increase interactions for a positive impact on innovative performance and continuous innovation [90]. Efforts by governments in tackling poverty reduction should focus on improving food security using innovations and other interventions since the pathway lies in improved food security outcomes.

Secondly, to sustain the gains of innovations in food security among food and cash crop farmers, it is necessary to strengthen and sustain the government of Ghana's flagship programme Planting for Food and Jobs (PFJ). The PFJ programme aims at improving food and income security among farm households, through productivity increase and job creation [91]. The policy is anchored on five main modules - food crops (PFJ), planting for export and rural development (PERD), greenhouse technology villages (3 Villages), rearing for food and jobs (RFJ), and agricultural mechanization services (AMSECs). The food crop module focuses on (1) distribution of subsidized fertilizer; (2) seed access and development; (3) extension services provisioning; (4) marketing; and (5) e-Agriculture to improve crop productivity. Therefore, investment towards the success of this policy intervention will ensure that food and income security is improved as well as linkages to agroprocesssing are promoted and strengthened.

Moreso, the findings of our study imply that the pathway towards poverty reduction from any intervention is through food security improvement as innovations that consistently impacted on food security in both crop systems resulted in non-poor outcomes. This is to say that government's interventions aimed at improving food security should be prioritized if poverty reduction is the ultimate goal. The PFJ is a typical intervention in Ghana that can have such potential. The success of this policy may also be enhanced through linkage to the One-District-One-Factory (1D1F) policy, another intervention aimed at developing the agricultural value chain, creating jobs and reducing poverty. Therefore, given the context of our findings and the existing policy initiatives by the government, paying particular attention to such government interventions will create a pathway towards promoting food and income security, job creation, and subsequently poverty reduction. The findings further imply that the 1D1F will work towards reducing poverty if the PFJ programme works due to its direct link with food security.

Finally, our results imply that with the right investment in innovations, paying particular attention to bundles of innovations and not single regimes, Ghana is more likely to achieve the SDGs that focus on zero hunger (SDG 1) and poverty reduction (SDG 7). Furthermore, improving and expanding access to financial services, extension services and markets is imperative for poverty reduction for very poor households. Policy interventions should therefore incorporate favourable financing tools and programmes, especially for poorer households. The findings of this study can be adapted to countries with similar agricultural landscape whereby policies could target food and income security improvement and expansion in markets, financial and extension services in contributing towards poverty reduction.

5. Conclusion, key contribution to literature, and study limitations

Most studies have focused on single agricultural innovations and their impact on household welfare. Yet, there is limited understanding of how multiple innovations across different farming systems influence household welfare outcomes. This paper assessed the effect of multiple innovations and farmers' interaction in the agricultural innovation system on income, poverty, and food security. Using the FGT indices and the multinomial treatment effect models, the study concludes that cocoa farmers are less poor compared to maize farmers. However, adopting the full set of multiple innovations and increasing innovation system interactions, results in non-poor outcomes among maize-growing households, compared to cocoa. Though the effects of innovations are not being witnessed as expected, welfare gains are significant from adopting informational innovation and the combination of informational and improved seeds for both maize and cocoa farming households. Non-poor outcomes are also associated with markets, financial, and extension services interaction for the maize-growing households. Interactions in the agricultural innovation system as a whole result in non-poor effects for maize-growing households and the pooled households, signifying the potential role AIS can play towards poverty reduction, among agricultural households. The contribution of innovation and innovation system interaction to poverty reduction is significant among maize households compared to cocoa households. Given that maize households are poorer compared to cocoa, the findings suggest innovation and innovation system interactions can help move these households out of poverty if properly harnessed.

The study has contributed to bridging the methodological gap in this area with actor interaction in the innovation system being quantified and their effects on various welfare indicators analyzed. It also makes a significant contribution to the literature in terms of the food security (food expenditure) pathway to poverty reduction as innovations that significantly increased food security in either crop regimes, were associated with non-poor outcomes, irrespective of whether the household is a food or a cash crop growing one. The findings generally support the complexity of the innovation-poverty pathway, suggesting that not all innovations lead to poverty reduction. Nonetheless, however, complex it may be, if that innovation improves food security, poverty reduction may be assured.

Notwithstanding the contributions made by this study, it is not without limitations. We recognize that some proxies used such as mobile phones for informational innovation could be limiting since not all farmers use their phones to access agricultural information or connect to markets. Secondly, had the data used been primary data, the best proxy for the agricultural innovation system would have been the eigenvalues from the social network indices that would have been constructed as done in previous studies [39].

Future research can look at growth linkage and the employment effect of innovations. This will be to understand how technological progress in agriculture could have spill-over effects in other sectors. Another area of future research follows from the unexpected negative and non-significant effect of improved seeds on welfare. An experimental approach, such as the Randomized Controlled Trial (RCT) could be applied to unearth the real effect of improved seeds and what accompanying measures are required for the full effect to be realized. Why interaction in the cocoa innovation system does not improve the welfare of farmers is an area that requires further research. Given that the sector is yet to establish an innovation platform [85] that will facilitate interactions, it will be imperative to conduct a similar study of the sector after its establishment to assess its impact.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendices.

Appendix 1
Selection terms (λ) for the cocoa models

Factor loading parameter (λ)	Farm income model 1	Farm income model 2	Food-exp. model 1	Food-exp. model 2	Non-food exp. model 1	Non-food exp. model 2
λI_1S_0	−0.465***	−0.199	−0.278	−0.396***	−0.342*	−0.142
	(0.162)	(0.142)	(0.514)	(0.065)	(0.190)	(0.320)
λI_0S1	1.248**	0.027	−0.009	0.085	−0.142	0.392*
	(0.545)	(0.187)	(0.104)	(0.094)	(0.217)	(0.209)
λI_1S_1	−0.053	−1.223***	0.029	−0.065	0.279	−0.489
	(0.265)	(0.175)	(0.153)	(0.098)	(0.189)	(0.403)
			Poverty model 1			Poverty model 2
λI_1S_0			−0.074			−0.190***
			(0.259)			(0.069)
λI_0S1			−0.165			−0.171
			(0.239)			(0.123)
λI_1S_1			0.168			0.125
			(0.200)			(0.118)

Notes: Standard errors in parentheses; *Model 1= model with individual interactions; Model 2= model with the intensity of interactions as sum of the individual interactions.* $**p < 0.05$, $***p < 0.01$.
Source: Authors' computation based on the 2009/2010 and 2013/2014 GSPS data (2020)

Appendix 2
Selection terms (λ) for the maize models

λ	Farm income1	Farm income 2	Food security 1	Food security 2	Non-food exp. 1	Non-food exp. 2
$\lambda I_1P_0S_0$	0.246***	0.239**	−0.211**	−0.222**	0.072	0.059
	(0.086)	(0.108)	(0.098)	(0.088)	(0.133)	(0.138)
$\lambda\ I_0P_1S_0$	−0.014	0.010	0.039	0.053	0.316	0.260
	(0.100)	(0.131)	(0.162)	(0.156)	(0.257)	(0.248)
$\lambda\ I_0P_0S_1$	0.280***	0.302***	−0.190*	−0.181**	−0.279***	−0.279***
	(0.084)	(0.092)	(0.097)	(0.086)	(0.082)	(0.083)
$\lambda\ I_1P_1S_0$	−0.101	−0.152	−0.069	−0.068	−0.225	−0.277
	(0.092)	(0.095)	(0.109)	(0.111)	(0.290)	(0.262)
$\lambda\ I_1P_0S_1$	−0.134**	−0.124*	−0.049	−0.059	0.132*	0.137*
	(0.060)	(0.066)	(0.082)	(0.076)	(0.077)	(0.080)
$\lambda\ I_0P_1S_1$	0.154**	0.137*	−0.026	−0.028	0.149**	0.147**
	(0.069)	(0.072)	(0.059)	(0.055)	(0.071)	(0.072)

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Appendix 2 (*continued*)

λ	Farm income1	Farm income 2	Food security 1	Food security 2	Non-food exp. 1	Non-food exp. 2
λ $I_1P_1S_1$	−0.103 (0.077)	−0.107 (0.091)	0.064 (0.051)	0.060 (0.052)	0.106 (0.128)	0.108 (0.104)

	Poverty 1	Poverty 2
λ $I_1P_0S_0$	−1.003*** (0.135)	−0.987*** (0.143)
λ $I_0P_1S_0$	−0.028 (0.072)	−0.020 (0.070)
λ $I_0P_0S_1$	−0.207*** (0.067)	−0.204*** (0.073)
λ $I_1P_1S_0$	0.044 (0.045)	0.039 (0.043)
λ $I_1P_0S_1$	0.065* (0.034)	0.060 (0.036)
λ $I_0P_1S_1$	−0.160*** (0.060)	−0.158*** (0.061)
λ $I_1P_1S_1$	−0.020 (0.047)	−0.018 (0.048)

Standard errors in parentheses; *$p < 0.10$, **$p < 0.05$, ***$p < 0.01$.
Model 1 = model with individual actor interactions; Model 2 = model with the intensity of actor interactions as sum of the individual interactions.
Source: Authors' computation based on the 2009/2010 and 2013/2014 GSPS data (2020)

Appendix 3
Test of the validity of the instrument used for the treatment model in the cocoa model (falsification test)

Instrument	I_1V_0	I_0V_1	I_1V_1
Agricultural information	−0.619**	−0.296	−0.546**
	(0.287)	(0.359)	(0.263)
Constant	0.762***	−0.272	1.398***
	(0.264)	(0.332)	(0.244)
N	891		
Log likelihood ratio	−1109.020		
LR (χ^2)	28		
$P > \chi^2$	0.020		

Standard errors in parentheses; *$p < 0.10$, **$p < 0.05$, ***$p < 0.01$.

Appendix 4
Test of the validity of the instrument used for the maize treatment models (falsification test)

Variable	$I_1P_0S_0$	$I_0P_1S_0$	$I_0P_0S_1$	$I_0P_0S_1$	$I_0P_0S_1$	$I_0P_1S_1$	$I_1P_1S_1$
Agricultural information	0.562*	−2.049**	0.140	0.578**	0.270**	0.0690	0.415*
	(0.227)	(0.944)	(0.314)	(0.225)	(0.139)	(0.250)	(0.226)
Constant	−1.961**	1.318***	−0.391	1.269***	0.880***	0.585***	1.253***
	(0.794)	(0.193)	(0.270)	(0.194)	(0.204)	(0.214)	(0.194)
N							2595
Log likelihood							−4869.41
LR (χ^2)							42.80
$P > \chi^2$							0.000

Standard errors in parentheses; *$p < 0.10$, **$p < 0.05$, ***$p < 0.01$.

Appendix 5
Test of the validity of the instrument used for the Outcome models in maize (falsification test)

	Farm income		Food exp		Non-Food exp		Total exp		Povery	
	Coeff	SE	Coeff	SE	Coeff	SE	Coeff	SE	Coeff	SE
Agric_info	0.350	0.224	−0.008	0.145	0.513*	0.298	0.124	0.152	−0.029	0.403
Constant	5.769***	0.191	7.369***	0.124	5.796***	0.254	7.724***	0.130	0.118	0.344
N	124		124		124		124		124	
F (1,122)	2.44		0		2.96		0.66			

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Appendix 5 (*continued*)

	Farm income		Food exp		Non-Food exp		Total exp		Povery	
	Coeff	SE	Coeff	SE	Coeff	SE	Coeff	SE	Coeff	SE
P > F	0.121		0.956		0.08		0.417			
LR (χ^2)									0.01	
P>χ^2									0.94	

Standard errors in parentheses; *$p < 0.10$, **$p < 0.05$, ***$p < 0.01$.

Appendix 6

Test of the validity of the instrument used for the Outcome models in cocoa (falsification test)

	Farm income		Food exp.		Non-Food exp.		Total exp.		Poverty	
	Coeff.	SE	Coeff.	SE	Coeff.	SE	Coeff.	SE	Coeff.	SE
Agric_info	−1.472***	0.587	0.102	0.201	−0.230	0.396	−0.080	0.229	−0.327	0.505
Constant	6.982***	0.552	7.220***	0.189	6.748***	0.372	8.020***	0.215	0.223	0.474
N	153		153		150		153		153	
Wald χ^2	6.28		0.26		0.34		0.12			
LR (χ^2)									0.42	
P>χ^2	0.012		0.612		0.562		0.725		0.516	

Appendix 7

Other variables controlled for in the analysis

	Revenue model 1		Food exp. model 1		Revenue model 2		Food exp. model 2	
	Maize	cocoa	Maize	cocoa	Maize	cocoa	Maize	cocoa
HHsize	0.033***	0.018	0.053***	0.081***	−0.051***	−0.079***	0.037***	0.004
	(0.007)	(0.026)	(0.006)	(0.010)	(0.006)	(0.010)	(0.008)	(0.026)
Urban	−0.030	−0.338	0.009	0.037	−0.002	0.023	−0.048	−0.307*
	(0.064)	(0.256)	(0.052)	(0.064)	(0.052)	(0.063)	(0.067)	(0.172)
Year	0.563***	1.814***	0.183***	0.157	0.361***	0.370***	0.575***	1.037***
	(0.082)	(0.463)	(0.058)	(0.101)	(0.048)	(0.054)	(0.053)	(0.164)
Age	−0.003*	0.004	−0.004***	−0.007***	−0.004***	−0.006***	−0.004***	0.010**
	(0.001)	(0.004)	(0.001)	(0.002)	(0.001)	(0.002)	(0.001)	(0.005)
Education	−0.087*	0.097	0.053	0.049	0.047	0.027	−0.103**	0.083
	(0.048)	(0.151)	(0.041)	(0.055)	(0.040)	(0.054)	(0.052)	(0.140)
Gender	0.391***	0.092	−0.092**	−0.191***	−0.072*	−0.180***	0.436***	0.215
	(0.054)	(0.147)	(0.039)	(0.063)	(0.039)	(0.055)	(0.055)	(0.140)
Land tenure	−0.125***	0.315**	−0.079***	0.136**	−0.086***	0.133***	−0.130***	0.184
	(0.041)	(0.127)	(0.028)	(0.066)	(0.028)	(0.048)	(0.042)	(0.125)
Agric. info	0.152***	0.114	−0.008	0.054	−0.004	0.041	0.139***	0.105
	(0.048)	(0.152)	(0.031)	(0.059)	(0.031)	(0.055)	(0.050)	(0.157)
HH asset	0.024**	0.000	0.009***	0.004*	0.038	0.002	0.041	0.000
	(0.011)	(0.076)	(0.000)	(0.018)	(0.072)	(0.010)	(0.091)	(0.048)
Productivity	0.667***	0.883***	−0.000	0.743*	−0.012	0.002***	0.003**	0.019**
	(0.015)	(0.016)	(0.056)	(0.023)	(0.001)	(0.000)	(0.001)	(0.009)
	Non-food model 1		Total exp. Model 1		Non-food Model 2		Total exp. Model 2	
	Maize	cocoa	Maize	Cocoa	Maize	Cocoa	Maize	cocoa
HHsize	−0.059***	−0.078***	−0.063***	−0.102***	−0.064***	−0.100***	−0.060***	−0.088***
	(0.010)	(0.019)	(0.006)	(0.011)	(0.006)	(0.011)	(0.010)	(0.022)
Urban	1.108***	0.585***	0.489***	0.296***	0.486***	0.279***	1.108***	0.541***
	(0.107)	(0.133)	(0.064)	(0.084)	(0.064)	(0.083)	(0.106)	(0.134)
Year	0.488***	−0.083	0.155***	0.016	0.270***	0.127**	0.590***	0.062
	(0.093)	(0.184)	(0.057)	(0.120)	(0.038)	(0.064)	(0.057)	(0.119)
Age	−0.000	−0.002	−0.003**	−0.005**	−0.002**	−0.004**	−0.000	0.001
	(0.002)	(0.004)	(0.001)	(0.002)	(0.001)	(0.002)	(0.002)	(0.004)
Education	0.492***	0.168*	0.203***	0.120**	0.204***	0.086	0.504***	0.099
	(0.063)	(0.098)	(0.034)	(0.060)	(0.034)	(0.059)	(0.061)	(0.105)
Gender	−0.462***	−0.166*	−0.189***	−0.156**	−0.190***	−0.157**	−0.479***	−0.146
	(0.064)	(0.099)	(0.037)	(0.062)	(0.037)	(0.061)	(0.063)	(0.122)
Land tenure	0.177***	0.198**	−0.030	0.182***	−0.039	0.165***	0.168***	0.111
	(0.049)	(0.096)	(0.030)	(0.058)	(0.029)	(0.055)	(0.049)	(0.104)
Agric info	0.180***	−0.019	0.042	−0.007	0.042	−0.016	0.179***	−0.034
	(0.058)	(0.106)	(0.033)	(0.068)	(0.033)	(0.066)	(0.058)	(0.105)

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Appendix 7 (*continued*)

	Revenue model 1		Food exp. model 1		Revenue model 2		Food exp. model 2	
	Maize	cocoa	Maize	cocoa	Maize	cocoa	Maize	cocoa
HH asset	0.019***	0.002**	0.000***	0.005***	0.051***	0.000***	0.000***	0.000**
	(0.002)	(0.000)	(0.000)	(0.001)	(0.014)	(0.000)	(0.000)	(0.000)
Productivity	0.016	0.029*	−0.037	0.026	−0.029	0.009**	0.008	0.010***
	(0.024)	(0.003)	(0.054)	(0.022)	(0.020)	(0.004)	(0.012)	(0.001)

	Poverty model 1		Poverty model 2		Poverty pooled	
	Maize	Cocoa	Maize	Cocoa	Model 1	Model 2
HHsize	0.032*** (0.004)	0.065*** (0.007)	0.032*** (0.004)	0.062*** (0.007)	0.040*** (0.003)	0.037*** (0.003)
Urban	−0.190*** (0.034)	−0.088* (0.045)	−0.188*** (0.034)	−0.086* (0.045)	−0.163*** (0.033)	−0.139*** (0.029)
Year	−0.091** (0.038)	0.012 (0.081)	−0.181*** (0.024)	−0.134*** (0.044)	−0.092** (0.042)	−0.164*** (0.023)
Age	0.001** (0.001)	0.002 (0.002)	0.001* (0.001)	0.002* (0.001)	0.002*** (0.001)	0.002*** (0.001)
Education	−0.107*** (0.022)	−0.051 (0.040)	−0.108*** (0.022)	−0.049 (0.043)	−0.117*** (0.035)	−0.086*** (0.023)
Gender	0.137*** (0.027)	0.073* (0.044)	0.135*** (0.027)	0.088** (0.038)	0.138*** (0.024)	0.120*** (0.023)
Land tenure	0.007 (0.019)	−0.059 (0.055)	0.011 (0.019)	−0.056 (0.036)	−0.023 (0.017)	−0.023 (0.016)
Agric info	−0.015 (0.021)	−0.057 (0.045)	−0.020 (0.021)	−0.051 (0.039)	−0.035 (0.023)	−0.025 (0.019)
HH asset	−0.000*** (0.000)	−0.009*** (0.003)	−0.052*** (0.001)	−0.001*** (0.000)	−0.003*** (0.000)	−0.002*** (0.000)
Productivity	−0.006 (0.003)	−0.052** (0.002)	−0.008* (0.004)	−0.006*** (0.000)	−0.004 (0.005)	−0.003 (0.012)

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